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Ionospheric Observation of Enhanced Convection-Initiated Gravity Waves During Tornadic Storms

R. J. Hung

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I. INTRODUCTION

In the laboratory experiments Townsend (1964), Deardorff et al. (1969), Willis and Deardorff (1974), and Adrian (1975) observed that gravity waves were excited when convective elements overshot the top of the mixed layer and penetrated a short distance upward into the stable region. Curry and Murty (1974), Gossard and Sweezy (1974), Stull (1976), etc., have suggested that thunderstorms or fronts could excite gravity waves in the atmosphere. Einaudi and Lalas (1975) indicated that gravity waves can propagate upward through the atmosphere and stimulate cloud growth. In the observation of equatorial ionosphere, Röttger (1977) showed the association of gravity waves with penetrative cumulus convection. Matsumoto and Akiyama (1969) contended that gravity waves were responsible for the pulsating tendency of winter and summer convective storms in Western Japan. Uccellini (1975) proposed that gravity waves were an important mechanism for triggering severe convective storms. He also suggested that much could be learned about the development of thunderstorms by studying atmospheric gravity waves.

There have been many observations of atmospheric gravity waves. Gossard and Munk (1954) detected gravity waves aloft using surface-based pressure and wind velocity sensors. Bean et al. (1973) used FM-CW radar; Browning et al. (1973) employed high-power pulsed Doppler radar to observe gravity waves. In recent years, CW Doppler soundings of F-region ionosphere have been used to detect gravity waves apparently associated with severe weather and thunderstorms (Baker and Davies, 1969; Prasad et al., 1975; Smith and Hung, 1975; Georges, 1976; Hung and Smith, 1977a; Hung and Smith, 1977b, etc.). These studies revealed that quasi-sinusoidal

oscillations, with two harmonic periods, 3 to 5 minutes and 6 to 9 minutes, are observed when thunderstorms with cloud tops (radar heights) in excess of about 12 km are present within a radius of several hundred kilometers of ionospheric reflection points.

Recently, gravity waves associated with tornadic storms and hurricanes have been observed (Hung et al., 1978a; Hung and Smith, 1978). These observations were made with a high frequency CW Doppler array system in which radio receivers located at a central site, NASA/Marshall Space Flight Center, monitored signals transmitted from three independent remote sites on three sets of frequencies and reflected off the ionosphere approximately half way between the transmitter and receiver site. When the electron density in the ionosphere is disturbed and fluctuated, the total phase path of the radio signal changes and the instantaneous frequency of the radio echo are also shifted. During time periods with weather activity, wave-like disturbances are observed in the Doppler records.

Gravity waves are also important in understanding the behavior of ionospheric irregularities (Hines, 1960). The ionospheric irregularities known as TID's (travelling ionospheric disturbances) are a manifestation of gravity waves in the form of ionization in the F region. TID's, in general, can be divided into two categories, large-scale TID's and medium-scale TID's, based on the characteristics of wave propagation (e.g., Kato, 1976).

The large-scale TID's have been identified, from the ionization version of the gravity waves, to be the production of Joule heating and of Ampere mechanical force at the aurora zone during magnetic substorms (e.g., Chimonas and Hines, 1970; Testud, 1970). The excitation of large-scale TID's is dependent upon the intensity of the magnetic activity.

Titheridge (1971) has shown that Kp > 5 is a necessary condition, and Testud (1970) has proposed from his observation of the F-region neutral wind that the large-scale gravity waves occur when $\sum_{24}$ Kp > 16. Here Kp is the 3-hourly magnetic index and $\sum_{24}$ is its sum for a day.

Medium-scale TID's have been observed more often than large-scale TID's and may be excited by various sources, including meteorological severe storm activity and magnetic disturbances. In the present study, the analysis of Doppler records of the ionospheric fluctuations during the time period of tornado activity indicates that atmospheric gravity waves (medium-scale TID's) with two harmonic wave periods have been detected, one with a period of 10 to 15 minutes and the other with a period of 25 to 30 minutes. The horizontal phase velocities are 90 to 220 m/sec.

During the day of the extreme tornado outbreak of April 3, 1974, large-scale TID's were observed at 2200-2400 UT in addition to medium-scale TID's associated with tornadoes. The wave period of the observed large-scale TID's was 36 minutes, and the horizontal phase velocity was 350 m/sec. Davies and Da Rosa (1969) indicate that the maximum speeds observed for large-scale TID's are in the range of 500 to 1000 m/sec with the minimum near 300 to 400 m/sec, which are larger than the observed medium-scale TID's associated with tornado activity. The geomagnetic index shows that Kp was 4 during 2100-2400 UT and was 6 during 1800-2100 UT, April 3, 1974. It was also indicated that $\sum_{24}$ Kp was 36 on April 3, 1974.

Identification of the sources of these waves has been attempted using a reverse ray tracing technique. Comparison of the computed probable sources of the waves (medium-scale TID's) based on fifteen observed events with the locations and times of the actual tornado touchdowns has shown that the signals were observed more than one hour before the tornadoes

touched down. Results for gravity waves associated with hurricanes show the computed sources of waves to be located along the storm track and more than three hours in advance of the location of the storms.

For the case of large-scale TID's, it was found that the computed location of the wave source was in the auroral zone at auroral altitude. The wave traveling time from the probable source of the wave to the receivers at Huntsville, Alabama, took roughly 3 hours 20 minutes. This means that the gravity waves were excited during 1800-2100 UT in which Kp was 6. This result verifies the conclusion drawn by Kato (1976).

Two graduate students completed their degrees which were supported by the present grant. Names and topics of these are as follows:

(A) T. Phan

Topic of Thesis: Observation of Ionospheric Disturbances During Time Periods of Tornadic Storms

Degree Conferred: Master of Science in Engineering

(B) J. P. Kuo

Topic of Thesis: Study of Acoustic-Gravity Wave Propagation During Time Periods of Thunderstorms and Hurricanes

Degree Conferred: Master of Science in Engineering

(C) D. C. Lin

Topic of Thesis: Study of Severe Weather Activity by Using Remote Sensing Techniques

Degree Conferred: Master of Science in Engineering

The present support also resulted in the following publications:

(1) Hung, R. J., Observation of Upper Atmospheric Disturbances Caused by Hurricanes and Tropical Storms, Space Res., 17, 205-209, 1977.

(2) Hung, R. J., and R. E. Smith, Study of Stratospheric-Ionospheric Coupling During Time Periods of Thunderstorms and Tornadic Storms, Space Res., 17, 210-216, 1977.

(3) Hung, R. J., Prediction of Tornadoes and Typhoons (Hurricanes) by Using Gravity Wave Diagnostics, Atmosph. Sci., 4, 48-65, 1977.

(4) Hung, R. J., and R. E. Smith, Ray Tracing of Gravity Waves as a Possible Warning System for Tornadic Storms and Hurricanes, J. Appl. Meteor., 17, 3-11, 1978.

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(6) Hung, R. J., T. Phan and R. E. Smith, Ionospheric Doppler Sounder for Detection and Prediction of Severe Storms, AIAA Journal, 16, 763-766, 1978.

(7) Hung, R. J., J. P. Kuo and R. E. Smith, Gravity Waves from Hurricane Eloise, Proc. Hurricanes and Tropical Meteorology, ed. by J. M. Pelissier, pp. 630-635, Am. Meteor. Soc., Boston, Mass., 1978.

(8) Hung, R. J., and J. P. Kuo, Ionospheric Observation of Gravity Waves Associated with Hurricane Eloise, J. Geophys., 45, 67-80, 1978.

(9) Hung, R. J., and R. E. Smith, Dynamics of Severe Storms Through the Study of Thermospheric-Tropospheric Coupling, J. Geomag. Geoelect., 31, 183-194, 1979.

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(11) Hung, R. J., T. Phan, and R. E. Smith, Coupling of Ionosphere and Troposphere During the Occurrence of Isolated Tornadoes on November 20, 1973, J. Geophys. Res., 84, 1261-1268, 1979.

(12) Hung, R. J., T. Phan, D. C. Lin, R. E. Smith, R. R. Jayroe and G. S. West, Gravity Waves and GOES IR Data Study of an Isolated Tornadic Storm on 29 May 1977, Month. Wea. Rev., 108, 456-464, 1980.

II. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

Our Doppler sounder array system consists of three sites with nine field transmitters operating at 4.0125, 4.759 and 5.734 MHz. These sites are located at Ft. McClellan, Alabama (33° 44' N and 85° 48' W); TVA, Muscle Shoals, Alabama (34° 46' N, and 87° 38' W); and TVA, Nickajack Dam, Tennessee (35° 01' N and 85° 38' W), with receivers located at NASA/Marshall Space Flight Center, Alabama (34° 39' N and 86° 40' W). Since each of the three transmitters uses the same nominal frequency, the actual frequencies must be slightly different so that they can be distinguished from each other at the receiver. At the receiving station, the oscillators have been set exactly at the nominal frequencies, so that in the absence of Doppler variations the offsets of the transmitter oscillators are equal to the beat frequencies.

During the extreme tornado outbreak of April 3, 1974, we observed wave-like fluctuations with wavelengths on the order of 100 km. These observed traveling ionospheric disturbances (TID's) associated with severe storms belong to medium-scale TID's in contrast with large-scale TID's associated with geomagnetic activity initiated at the aurora zone (Kato, 1976). The observed data were subjected to both power spectral density analysis and cross-correlation analysis.

The power spectral density analysis of observations sometimes revealed more than one peak. When this occurred, Butterworth's digital filter (Otnes, 1968) was applied to band pass the peaks. As an example, Figures 1, 2 and 3 show results of power spectral density analyses of ionospheric disturbances from the transmitters at Muscle Shoals, Alabama; Ft. McClellan, Alabama; and Nickajack Dam, Tennessee,

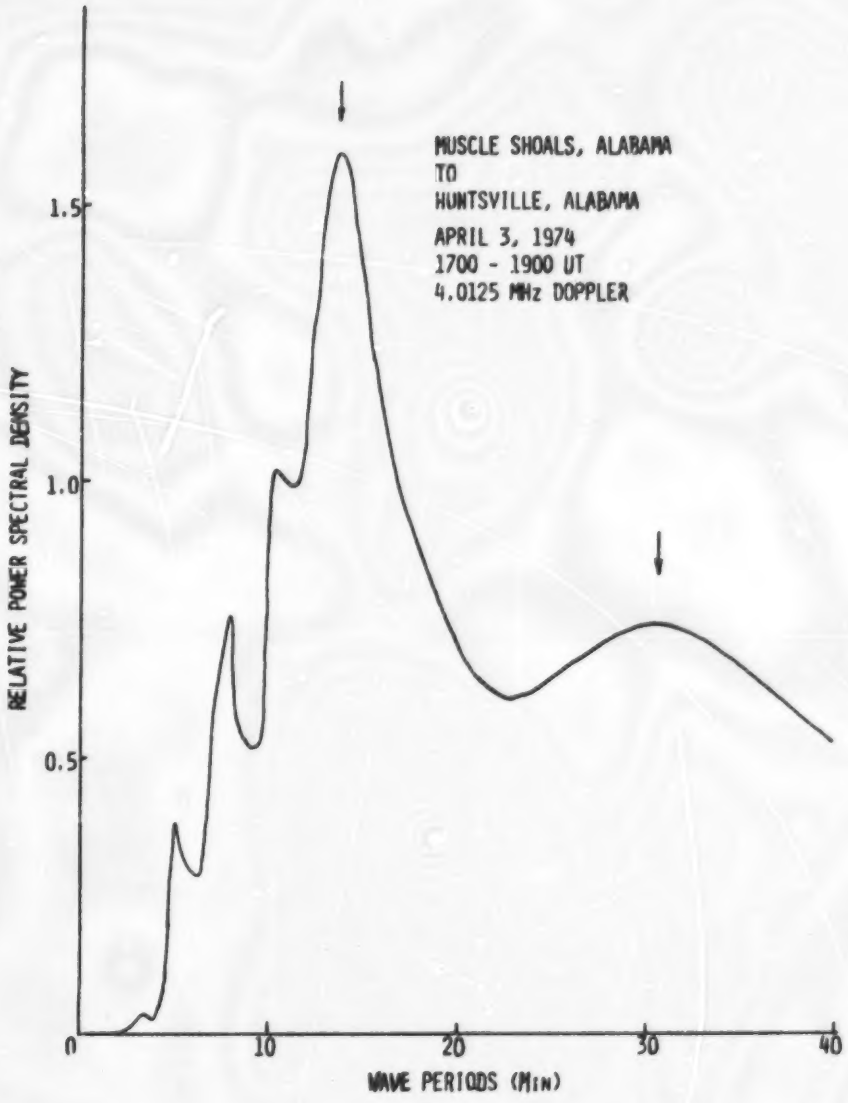

Figure 1. Power spectral density of ionospheric disturbances of Muscle Shoals station during 1700-1900 UT, April 3, 1974.

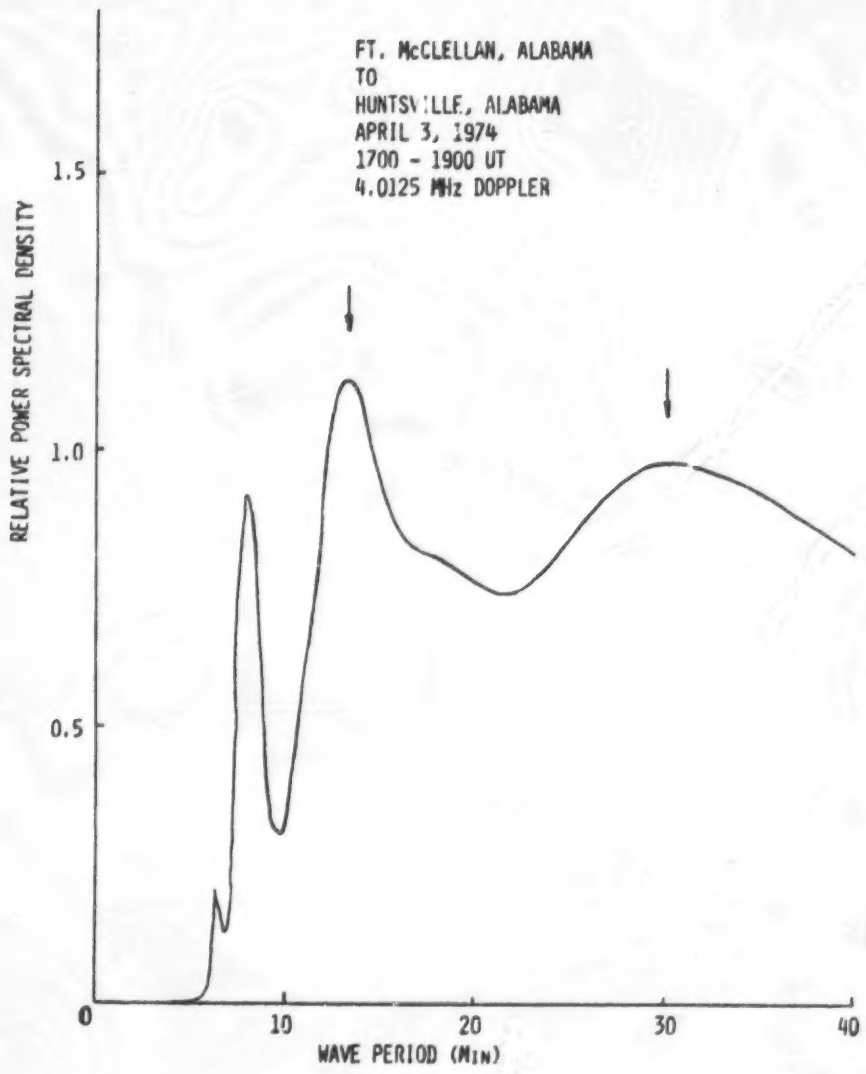

Figure 2. Power spectral density of ionospheric disturbances of Ft. McClellan station during 1700-1900 UT, April 3, 1974.

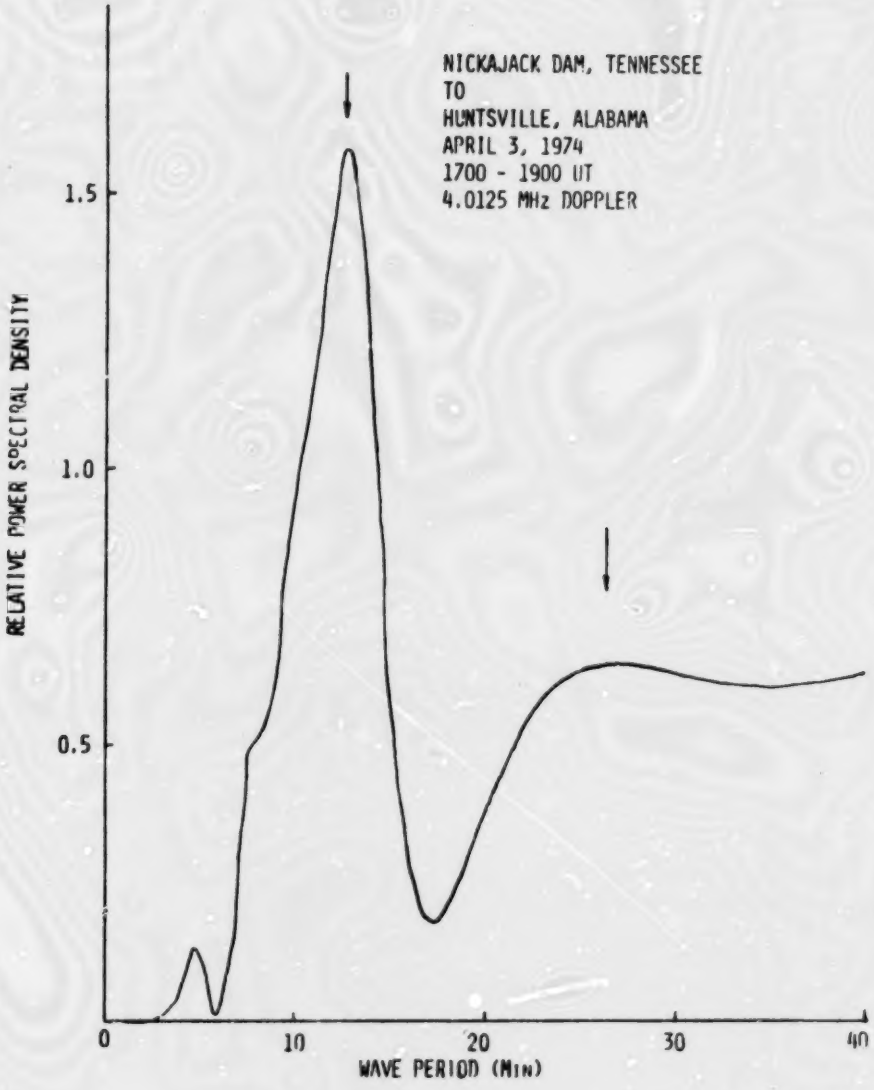

Figure 3. Power spectral density of ionospheric disturbances of Nickajack Dam station during 1700-1900 UT, April 3, 1974.

to the receivers at Huntsville, Alabama, respectively, without using the digital filter, at the observation time 1700-1900 UT. Two peaks resulted from each of the power spectral density analyses with a major peak around 13 minutes. Figures 4, 5, and 6 show similar power spectral density results for the observation time, after using digital filter with a 21-50 minute band pass. The average period of these longer wave period disturbances is around 29 minutes.

Cross-correlation analysis is accomplished. As an example, Figure 7 shows cross-correlograms during the time interval of observation, 1700-1800 UT. The notation M-F, shown in Figure 7, denotes the time delay of signal arrival between Muscle Shoals and Ft. McCelllan; notation N-F, the time delay between Nickajack Dam and Ft. McClellan; and notation N-M, the time delay between Nickajack Dam and Muscle Shoals. The horizontal wave vector and horizontal phase velocity of the disturbances are calculated from cross-correlograms. The accuracy of the determination of the azimuthal angle of wave propagation is within 10^{o}, and horizontal phase velocity is within 10 percent of derivation in this setup.

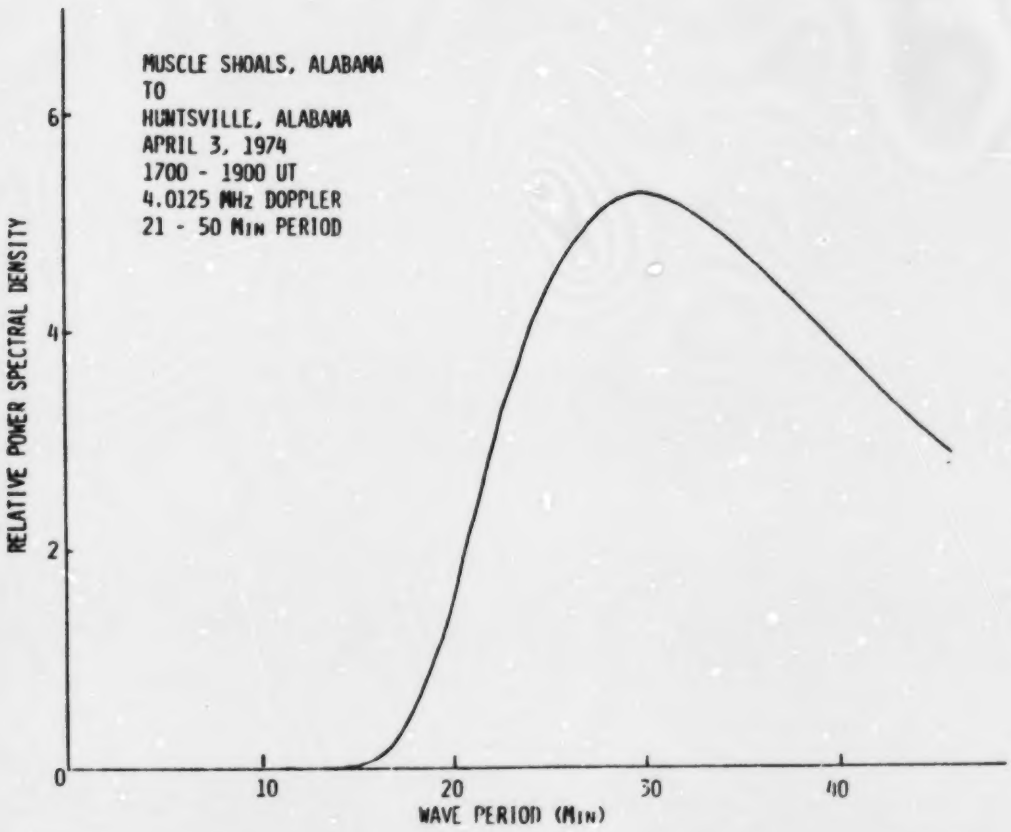

Figure 4. Power spectral density of ionospheric disturbances (bandpass filtered 21-50 minutes) of Muscle Shoals station during 1700-1900 UT, April 3, 1974.

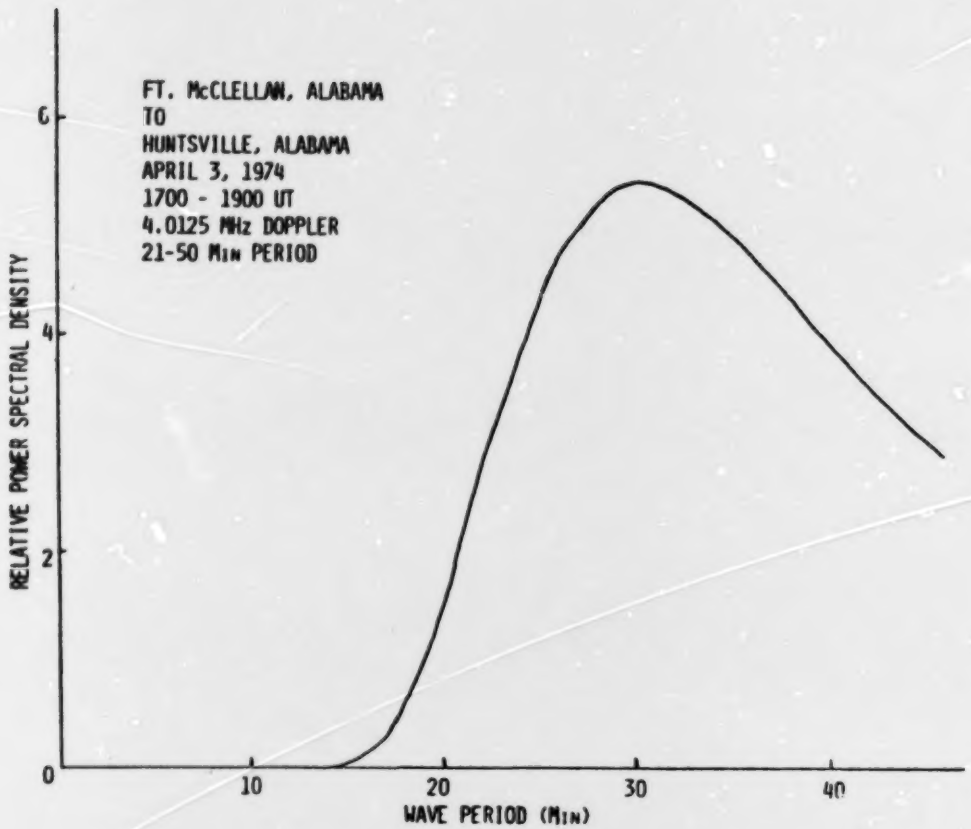

Figure 5. Power spectral density of ionospheric disturbances (bandpass filtered 21-50 minutes) of Ft. McClellan station during 1700-1900 UT, April 3, 1974.

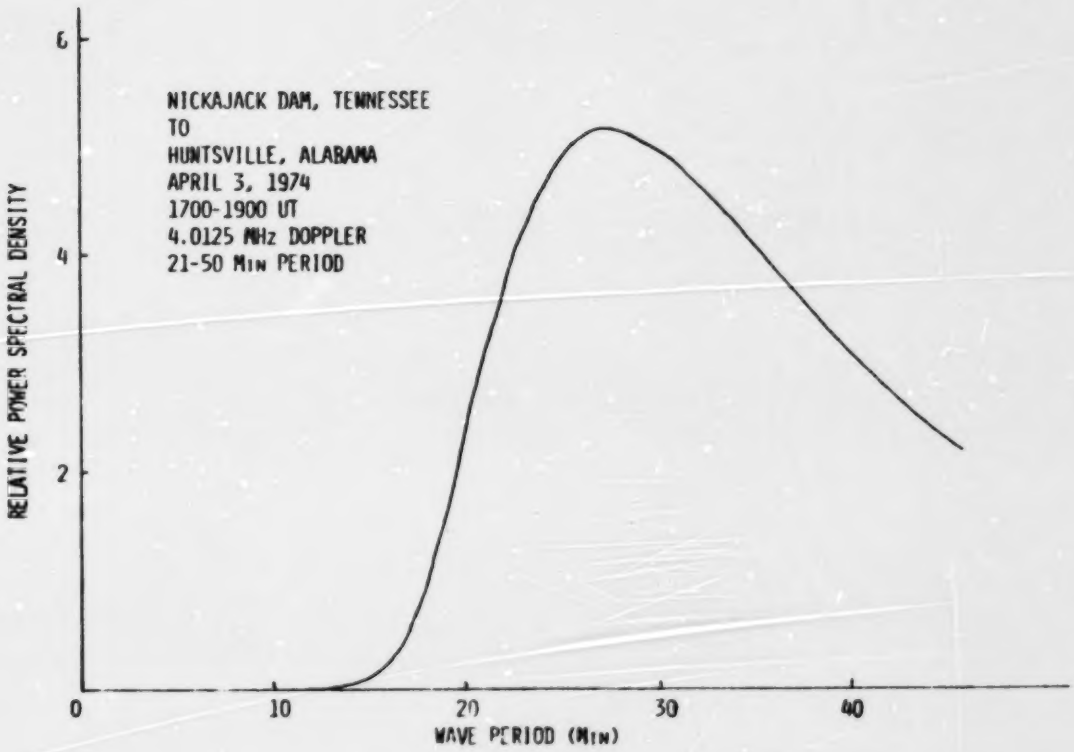

Figure 6. Power spectral density of ionospheric disturbances (bandpass filtered 21-50 minutes) of Nickajack Dam station during 1700-1900 UT, April 3, 1974.

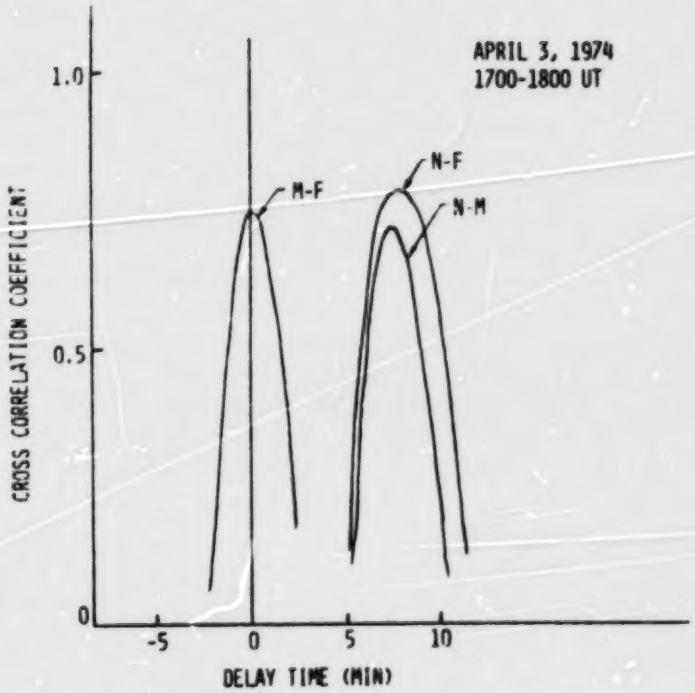

Figure 7. Cross-correlograms from Nickajack Dam (N), Muscle Shoals (M), and Ft. McClellan (F) at time period of observation 1700-1800 UT, April 3, 1974.

III. RAY PATH COMPUTATION

The characteristics of atmospheric acoustic-gravity waves are described by the dispersion relation which for an isothermal atmosphere has the form (Hines, 1960):

$$\left(1 - \frac{\omega_a^2}{\omega^2}\right)^{-1} \left[k_x^2 \left(1 - \frac{\omega_b^2}{\omega^2}\right) + k_z^2\right] = \frac{\omega^2}{a^2} \qquad (1)$$

where ω denotes angular wave frequency; k_x, the horizontal wave number; k_z, the vertical wave number; a, the speed of sound; γ, the ratio of specific heats; g, the acceleration due to gravity; $\omega_a = \gamma g/2a$, the acoustic cutoff frequency; and $\omega_b = (\gamma-1)^{1/2}\, g/a$, the buoyancy frequency. In the real atmosphere, the buoyancy frequency is given by

$$\omega_b = \left[\frac{(\gamma-1)\, g^2}{a^2} + \frac{g}{a^2}\,\frac{da^2}{dz}\right]^{1/2} \qquad (2)$$

where ρ is the density of the medium.

The location of the source of the wave generating mechanism can be computed by using a ray tracing analysis if the wind velocity is comparable to the group velocity of the waves and the background medium is inhomogeneous. Theoretical discussions of group rays of acoustic-gravity waves have been carried out by Bretherton (1966), Jones (1969), Cowling et al. (1971) and Bertin et al. (1975). These discussions indicate that the geometrical optics approximation seems valid under the conditions discussed. The wave propagated is assumed to be locally plane so that the local dispersion relation, Eq. (1), is satisfied.

Ray tracing, thus, could be carried out by following the group velocity direction in a wind-stratified model atmosphere.

The effect of the wind can be taken into account by considering the time-space transformation given by the Galilean transformation

$$\underset{\sim}{r}' = \underset{\sim}{r} - \underset{\sim}{u}t, \quad t' = t$$
$$\omega' = \omega - \underset{\sim}{k} \cdot \underset{\sim}{u}, \quad \underset{\sim}{k}' = \underset{\sim}{k} \tag{3}$$

where $\underset{\sim}{r}$ and t denote the position vector and time, respectively. All quantities expressed in unprimed form are observed in the stationary coordinate system, and those in primed form are in the coordinate system moving with the medium with a constant horizontal velocity $\underset{\sim}{u}$. To compute a wave packet incident from below in the presence of horizontal wind shear, we can assume that the medium can be thought of as being made up of horizontally stratified layers. In each layer, a dispersion relation, Eq. (1), with ω replaced by ω' is satisfied. The kinematic boundary condition requires that the horizontal wave vector be matched from layer to layer, i.e.,

$$(\underset{\sim}{k}_x)'_i = (\underset{\sim}{k}_x)'_o = \underset{\sim}{k}_x \tag{4}$$

where $(\underset{\sim}{k}_x)'_o$ is horizontal wave number at incidence and $(\underset{\sim}{k}_x)_i$ is that in the ith layer, i = 1, 2, 3 .... This condition, Eq. (4) together with the Galilean transformation, Eq. (3) indicates that the horizontal wavelength remains constant while the wave frequency in the ground-based coordinate system is shifted in the presence of background wind as the wave propagates from the stratosphere up to the ionosphere.

It is known that, in a lossless, transparent medium, energy propagates in the direction of the group velocity, $\underset{\sim}{v}_g$ (e.g., Yeh

and Liu, 1972). This direction is termed the ray direction. In general in an anisotropic medium the ray direction is different from that of the wave vector $\underset{\sim}{k}$. The definition of group velocity is

$$\underset{\sim}{v}_g = \nabla_{\underset{\sim}{k}}\, \omega(\underset{\sim}{k}) . \tag{5}$$

It is obvious that $\underset{\sim}{v}_g$ is normal to the surface $\omega(\underset{\sim}{k})$ = constant which is the solution of the dispersion relation, Eq. (1) for atmospheric waves, with a fixed frequency. For the presence of horizontal wind, with the substitution of Eqs. (1), (3) and (4) in Eq. (5), the expressions for the group velocity of the waves in the moving frame of reference yield

$$v'_{gz} = - \frac{a^2\, \omega'\, k'_z}{a^2\, (k_x^2 + k_z'^2) - 2\omega'^2 + \omega_a^2} \tag{6}$$

$$\underset{\sim}{v}'_{gx} = \frac{(\omega_b^2 - \omega'^2)\, a^2\, \underset{\sim}{k}_x}{\left[a^2\, (k_x^2 + k_z'^2) - 2\omega'^2 + \omega_a^2\right]\omega'} . \tag{7}$$

In the stationary frame, the corresponding group velocity then becomes

$$v_{gz} = v'_{gz} \tag{8}$$

$$\underset{\sim}{v}_{gx} = \underset{\sim}{v}'_{gx} + \underset{\sim}{u} . \tag{9}$$

The group ray in $\underset{\sim}{r}$ - space is possible to compute by integrating

$$\frac{d\underset{\sim}{r}}{dt} = \underset{\sim}{v}_g , \tag{10}$$

which is the group ray trajectory of the waves. Thus, ω and $\underset{\sim}{k}$ propagate with $\underset{\sim}{v}_g$, while the phase front propagates with $\omega/\underset{\sim}{k}$.

In this computation, the neutral wind is treated as constant in each slab of the atmosphere considered. The values of ω_a, ω_b and a are calculated for each altitude from the parameters of the U. S. Standard Atmosphere (1962). The profiles of the neutral winds are established using data from the following two sources: (1) wind profiles above 100 km altitude are computed from the atmospheric wind model proposed by Kohl and King (1967); (2) at an altitude below 90 km, wind profiles are obtained from meteorological rocketsonde data at Cape Kennedy, Florida. For example, Figure 8 shows a computed vertical wind profile from the wind model for the zonal component (East-West direction) at 1700 UT, April, 1974. Figure 9 shows a computed vertical wind profile of the meridional component (North-South direction) from the wind model at 1700 UT, April, 1974. Figure 10 is an observed vertical profile of the zonal wind component from meteorological rocketsonde data at 1700 UT, April 3, 1974, at Cape Kennedy, Florida. Figure 11 is a similarly observed vertical profile of the meridional wind component from meteorological rocketsonde data at the same time and same location.

The reverse ray tracing will start at the proper ionospheric height from where the radio wave reflected and continues to a lower limit of 10 km altitude. Wind profiles from Cape Kennedy, Florida, may not be very appropriate for making ray path computations for the Alabama and Tennessee areas during tornado activity. However, what we actually need for computation is wind profiles above 10 km altitude; the deviation of wind profiles between Alabama and Cape Kennedy, Florida may not be too

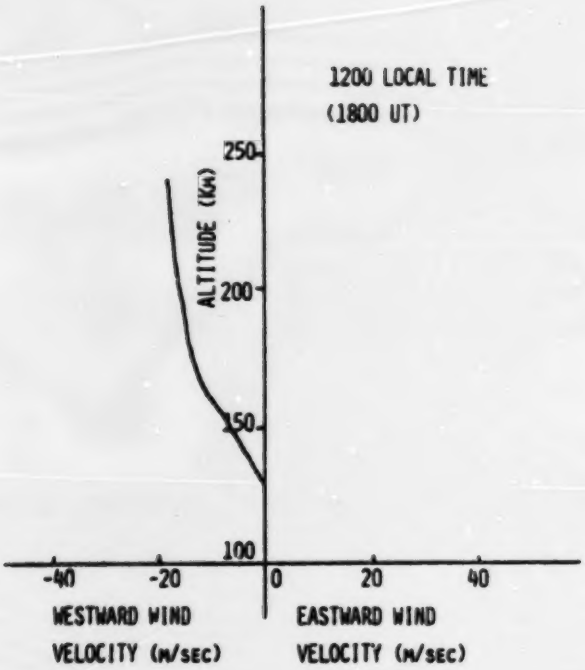

Figure 8. Computed vertical wind profile of the zonal component at 1200 local time (1800 UT) and 35 N latitude.

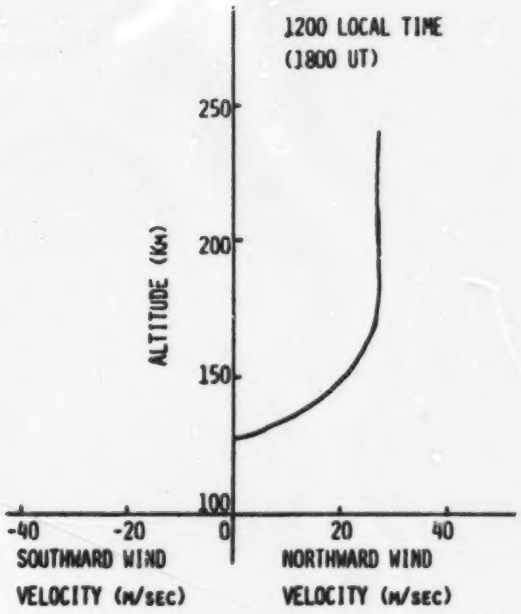

Figure 9. Computed vertical wind profile of the meridional component at 1200 local time (1800 UT) and 35 N latitude.

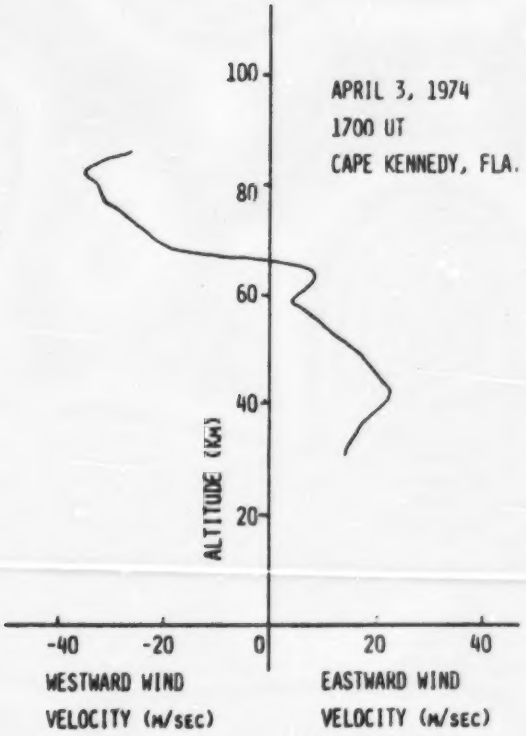

Figure 10. Observed vertical wind profile of the zonal component at 1700 UT, April 3, 1974, Cape Kennedy, Florida.

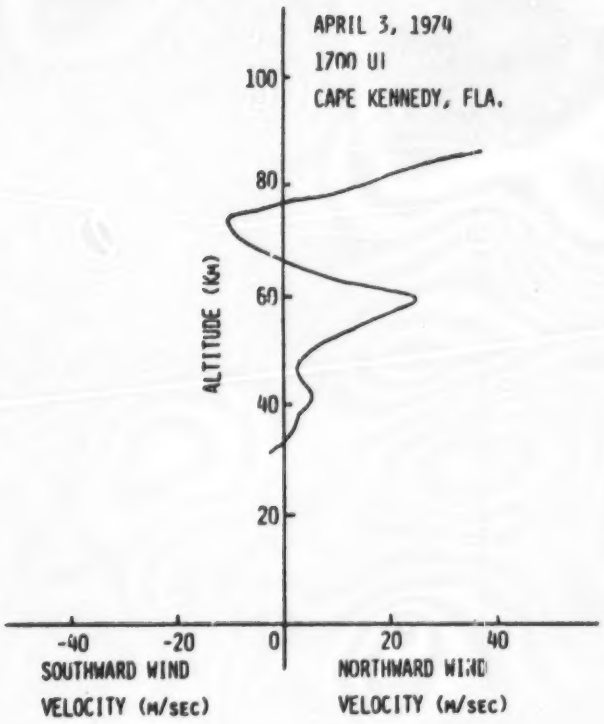

Figure 11. Observed vertical wind profile of the meridional component at 1700 UT, April 3, 1974, Cape Kennedy, Florida.

bad in this case. This can be checked from the computation of reverse ray tracing which shows that the effect of wind profiles below 50 km altitude is rather small since the maximum wind velocity in this region is small compared with the phase velocity of wave propagation. The reverse ray tracing is accomplished by integrating Eq. (10) with respect to reverse time coordinate. The wind direction shall not be reversed in this computation.

IV. SOURCES OF THE WAVES

The reverse ray tracing is started at an altitude of radio wave reflection height and continues as long as the calculation is possible, to a lower limit of 10 km altitude. For the purpose of the present study the geographic location of the point at which the calculation is terminated is referred to as the probable source. The probable sources of the gravity waves are then checked with the actual severe storm observations supplied by the National Climate Center (NCC), National Severe Storms Forecast Center (NSSFC), etc.

Examples of the method used in this study are given in papers published in open literature journals. The dates of gravity waves detected and the titles of the descriptions for three such examples are:

A. Coupling of Ionosphere and Troposphere During the Occurrence of Isolated Tornadoes on November 20, 1973. The paper was published in Journal of Geophysical Research, 84, 1261-1268, 1979.

B. Case Studies of Gravity Waves Associated with Isolated Tornadic Storms on 13 January 1976. The paper was published in Journal of Applied Meteorology, 18, 460-466, 1979.

C. Gravity Waves and GOES IR Data Study of an Isolated Tornadic Storm on 29 May 1977. The paper was published in Monthly Weather Review, 108 , 456-464, 1980.

V. CONCLUSIONS AND DISCUSSIONS

Ionospheric Doppler sounder observations during the time period with severe storm activity show a coupling between the troposphere and the ionosphere. Analyses of these observations indicate that acoustic-gravity waves propagating in the ionosphere are closely related to severe storm activity, with the waves apparently associated with tornadoes appearing to be excited where tornadoes touched down more than 1 hour later. Results for gravity waves associated with hurricanes show the computed sources of the waves to be located along the track and more than three hours in advance of the location of the storm.

Wave spectrum analyses of Doppler records from different time periods of observation, or data sampling times, indicate that the longer data sampling time makes better quality analysis of wave spectrum than the spectrum with the shorter data sampling time. Results from ray tracing computations show that the computed location of the wave sources with spectrum obtained from shorter data sampling time is reasonably good compared with the location of the wave sources with spectrum of a longer sampling time if the data sampling time is properly chosen. This conclusion suggests that we may be able to minimize our time period of observation for the purpose of developing remote sensing techniques for the detection of severe storms through the observation of gravity waves.

The dynamical behavior of intense convection associated with severe storms can be studied through the investigation of gravity wave generation mechanisms (Willis and Deardorff, 1974; Stull, 1976; Hung and Smith, 1979). The process of convective overshooting and ensuing collapse of the turret back into the cloud could generate outward and

upward propagating gravity waves (Black, 1977). Shenk (1974) made an extensive study of the relation between cloud top height variability and strong convective cells using geosynchronous satellite and U-2 airplane photographs. When the results of Shenk's analysis are used in the theoretical model proposed by Lighthill (1952; 1954; 1962; 1967), Townsend (1966; 1968) and Deardorff et al. (1969), it shows that gravity waves could be generated by tongues of turbulence penetrating above the turbulent convective zone and that waves with the same periods as those observed by the Doppler array are generated (Hung and Smith, 1979).

Comparison of the computed location of the wave sources associated with severe storms and conventional meteorological data, in particular the dynamical behavior of the squall line, shows that the wave sources were always located right on the squall line. Close examination of geosynchronous satellite photographs reveals that the overshooting turrets were occurring at the time that gravity waves were being excited (Hung, et al., 1979a, 1979b). Furthermore, satellite photographs also indicate that the movement of the overshooting turrets was in agreement with the movement of tornadoes and the convective turrets (Hung et al., 1980). Observation of gravity waves associated with severe storms from the ionospheric Doppler array, together with conventional meteorological data and satellite or aircraft photographs of convective overshooting turrets, will greatly contribute to the study of the dynamical behavior of severe storms.

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16. ABSTRACT

Atmospheric gravity waves can be generated by penetrative convection. Gravity waves associated with severe local thunderstorms, tornadoes, and hurricanes can be studied through the coupling between the ionosphere and the troposphere. Reverse group ray tracing computations of gravity waves observed by an ionospheric Doppler sounder array show that the wave sources are in the neighborhood of storm systems and the waves are excited prior to the storms. Analyses were made from more than 30 gravity waves detected in the ionosphere during severe storm activity. The results based on ray tracing computation and comparison between the computed location of the wave sources and conventional meteorological data show that the computed sources of the waves were near the actual touchdown of the tornadoes and the signals excited by the storms were more than 1 hour ahead of the time of the touchdown for gravity waves associated with the tornadoes; the computed sources were near the eye of the hurricane for gravity waves associated with the hurricanes. The results also illustrate that sources of gravity waves associated with the tornadoes were always located right on the squall line, and convective overshooting turrets from satellite photographs were occurring at the same locations and times when the gravity waves were being excited. The present study suggests that gravity wave studies with squall line and satellite photographs can be used to develop a remote sensing technique for detecting severe storms.

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